Thesis

A PINHOLE CAMERA FOR THE EVALUATION OF ATMOSPHERIC HAZE

BY

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BOSTON UNIVERSITY
GRADUATE SCHOOL

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by

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(A.B., Boston University, 1944)

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Approved

by

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FOREWORD

The author is indebted to Dr. Duncan E. Macdonald and Dr. Claus Aschenbrenner of the Boston University Optical Research Laboratory for their invaluable advice and assistance throughout the research and writing of this paper.

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I. INTRODUCTION

A. Statement of the Problem

One of the problems of major importance in aerial photography is that of haze or scattered light. Many methods have been devised to make transmission measurements and target contrast measurements as functions of type of weather, scattering particle size, wavelength, and path through scattering medium. However, little work has been done on determining the actual amount and distribution of this scattered light (as encountered from the position of the aerial photographer) as a function of observer position with respect to the sun.

This paper deals with an instrument and method of analysis to solve this problem by correlating film densities with relative illumination values determined by sensitometric means.

B. Atmospheric Haze

At all times and under all weather conditions there are present in the atmosphere, gas molecules and varying amounts of water in the form of vapor, droplets, or ice particles, and foreign matter such as dust, smoke, pollen, volcanic ash. When radiation in the form of sunlight passes through the atmosphere, light is scattered from the particles and molecules. The amount and type of scattering depends almost solely upon the size and distribution of these particles, upon the incident wavelength, and to a much lesser degree upon the dielectric constant of the material. This scattered light is called atmospheric haze. A brief discussion of the theory of scattering follows.

C. Scattering of Light by Particles

Newton gave consideration to the problem of the scattering of light by the atmosphere, and propounded a theory that accounted for the blue color of the sky. In the middle of the 19th century, Clausius stated that the reduction of intensity when light passes through the atmosphere could be represented by the equation:

$$I = I_o \, e^{-kd/\lambda^2} \qquad (1)$$

where I is the transmitted and I_o the initial intensity, d, the thickness of the layer, λ the wavelength, and k, a constant.

Brucke in 1853, and Tyndall in 1869, found that

when white light was passed into a transparent medium made turbid by very small particles, blue light was scattered away from the beam. Tyndall further found that the scattered light was polarized at right angles to the main beam. For a thorough investigation of the problem, we have to thank Lommel, and particularly Lord Rayleigh, who supplied the theory to corroborate experimental observations.

Rayleigh showed that under certain conditions the intensity of the scattered light varies inversely as the fourth power of its wavelength.

If the intensity of the initial beam is represented by I_o, and that of the transmitted beam by I,

$$I = I_o e^{-kd/\lambda^4} \qquad (2)$$

if the following conditions are fulfilled;

1. The particle size is small compared to the wavelength.
2. If the particle and wavelength are of equal magnitude, the equation holds only if the index of the medium and that of the particle are approximately equal.
3. Particle shape is that of a sphere.

It follows that the shorter wavelength, blue light is removed more readily by scattering than is red light. The scattered light will therefore appear blue, whereas the directly transmitted beam will assume an orange or reddish color owing to the removal of blue from it. Rayleigh showed

that the molecules of a gas such as air are able to scatter radiation in this way, and so explained the blue color of the sky. The theory also explains why distant haze and tobacco smoke appear blue, and shows why the color of the sun tends towards the orange when viewed through smoke or haze. The theory also shows that the predominant wavelength transmitted becomes longer as the path length increases, as is evidenced at sunrise and sunset when sunlight traverses a greater distance through the earth's atmosphere.

When the conditions for Rayleigh scattering are not fulfilled, the scattering function may become a special one, dependent on an irregular particle shape or upon diffraction effects. For particle size large with respect to the wavelength, regular surface reflection may occur.

It is seen that haze in the atmosphere is the combined effect of several types of scattering which may or may not be difficult to calculate theoretically. The relative dominance of one or the other type depends upon the composition of the atmosphere at the time of observation and the wavelength under observation.

D. Effect of Haze on Aerial Photography

Photographically, haze may be thought of as the total actinic energy incident on a film minus the image forming energy from the object. Scattered light is superimposed upon the image-forming light from objects, and the overall effect on the image is to reduce the contrast and the apparent brightness range. The greater the proportion of this

non-image forming light, the greater is the compression of the tonal range of the picture. This lowering of the contrast is in general detrimental, since recognizability of detail in photographs depends in a measure on the recorded contrast. If the haze were attributable only to Rayleigh scattering, most of the non-image forming scattered blue light could be removed or absorbed by use of a filter, and considerable increase in contrast could be attained. This practice, of course, is in wide use. Such benefit from a filter however, decreases sharply as the scattering changes from Rayleigh scattering to other forms that follow a lower power of λ .

E. Effect of the Position of the Sun

In daytime aerial photography, the sun is the source of all reflected and scattered light that makes up the total illumination on the film. Since scattering is not equal in all directions, but is dependent on the position of the source, particle index relative to medium, particle size, and wavelength, the position of the sun is important in determining the quality and amounts of non-image forming light that reach a camera objective in the air. Obviously the distribution of scattered light will not in general be symmetrical about a vertical axis, but will vary according to the sun position with respect to the camera. The path length for image-forming light increases as $1/\cos \alpha$, where α is the angle between the vertical axis and the

incident light. Thus the superimposed scattered light should increase with α, if the scattering were uniform. The purpose of the camera described herein is to make determinations of the actual distribution at various altitudes and under various types of weather conditions over a total field angle of 120 degrees.

Information thus attained will be applied to the design of correction filters for the spherical plate camera designed and constructed at Boston University Optical Research Laboratory.

II. THE PINHOLE CAMERA

A. Choice of Instrument

To carry out this study it was decided that a pinhole camera was an ideal instrument for several reasons.

1. A pinhole forms an image as a consequence of the rectilinear propagation of light. A small cone of light from a point of the object illuminates a corresponding element on the film. For every object point there is a corresponding conjugate, small area illuminated on the film, thus a real image is formed. The image is rendered in undistorted perspective, the angle subtended by the object with respect to the pinhole being equal with the angle subtended by the image at the pinhole. (see fig. 1.)
2. A lens actually has characteristics that are undesirable for the purpose of this research. First we have no need of a highly corrected image, since the actual exposures will deliberately be made to eliminate all image detail! (See Section III).

Second, it would be extremely difficult to design a lens to cover the desired 120 degrees, and if such a lens were produced, a calculation of the decrease in illumination over the focal plane due to inter-surface reflection losses, the $\cos^4$ loss, vignetting, would be difficult to calculate. The losses with the pinhole are relatively easy to calculate compared with the losses of a wide angle lens.

3. The cost of designing and constructing a pinhole camera would be relatively low.

The problem thus becomes one of designing a pinhole camera, setting up conditions for its use and method of analysis, and calculating correction factors to be applied before it can be used for actual haze evaluation.

B. <u>Design and Construction of the Camera</u>

At first it was planned to design the camera to accomodate a standard 9x9 inch aerial film magazine. However, for reasons of expediency and expense, without sacrifice in accuracy, it was built to fit a standard 8x10 inch cut film magazine. The requirements for the camera were:

1. That the field angle be 120 degrees.
2. That a shutter be provided that had a suitable open diameter for such a wide angle. The shutter need not be capable of exposure less than one second duration.
3. That the pinhole mount be designed to hold a one inch disk of thin metal in whose center the pinhole was located, in such a manner that the

Figure 1.

Image Formation By:

A. A Pinhole

B. A Lens

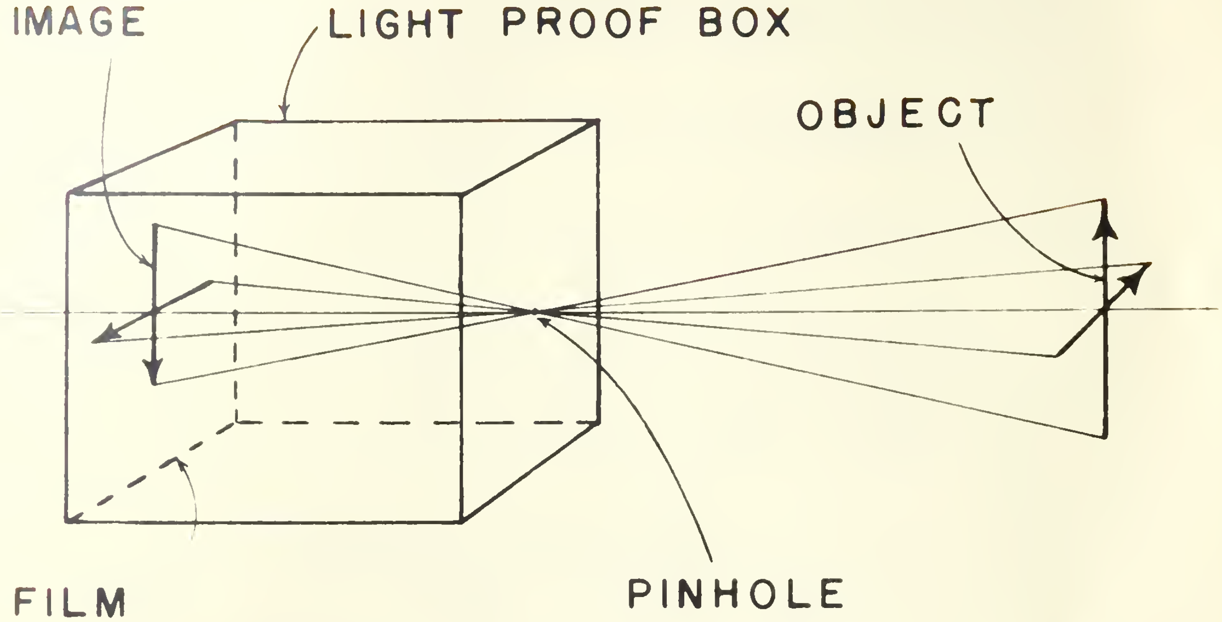

IMAGE FORMATION BY A PINHOLE

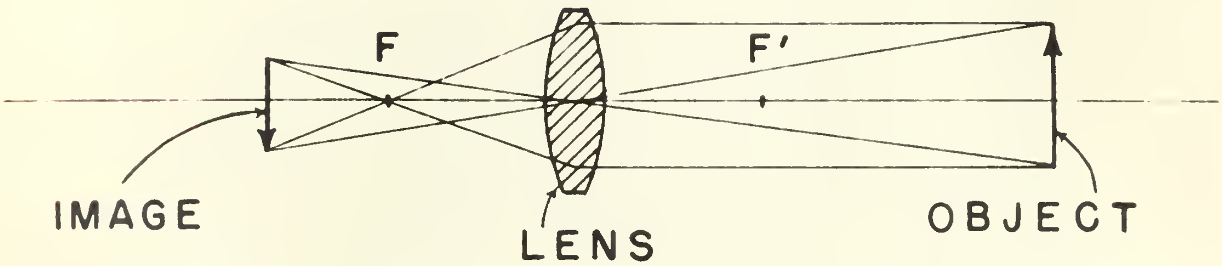

IMAGE FORMATION BY A LENS

disk maintain its position with respect to the film without buckling.

4. That it be possible to place a neutral density filter and various color filters directly behind the pinhole.
5. That it be possible to change pinholes and filters readily.
6. That a hood be provided to exclude stray light from outside the required angle.

To meet the requirement for the 120 degree field angle, the pinhole is located 2.310 (58.7mm) inches from the film plane as shown in Fig. 2.

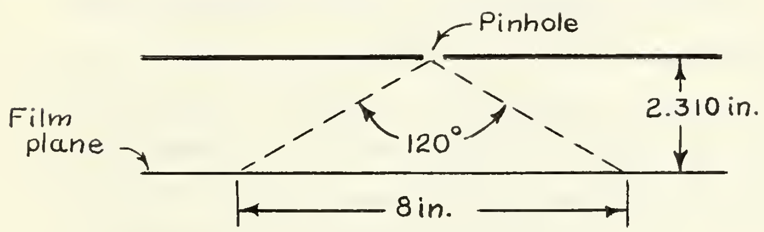

Figure 2.
Pinhole Location for 120° Field Angle

A shutter part, operated by a cable release, is built into the camera. The retaining ring (Part 11, Fig. 3) for the pinhole and filters is adjustable to allow ¼ inch variation in setting the focal distance. The hood (Part 12, Fig. 3.) is also adjustable. A small spanner wrench permits quick removal of the retaining ring holding the pinhole (Part 13) and filter (Part 10). All parts are blackened to minimize surface reflections. (See also figures 4,5, and 7.)

The slot in the magazine where the film holder is loaded into the camera was protected around the edges with felt to reduce possibility of light leaks. (This latter was not done until after a flight test had revealed the necessity for it).

Trunnions (detail A) are built into the side of the camera to allow its use with standard aerial camera mounts. Flight tests revealed this was not practical because it was impossible to obtain a clear view throughout the 120 degrees when the camera was placed in the standard mount.*

C. The Methods of Making The Pinhole

Requirements for the pinhole were:

1. It should be made in as thin a material as possible to keep vignetting losses at a minimum, yet the material must be rigid enough to prevent any fluctuations in the pinhole to film distance.
2. The hole should be as nearly circular as possible, straight-sided, and free from jagged edges and irregularities that might cause a non-symmetrical energy distribution over the film plane.

There are several techniques used in making small holes. One technique for very small holes consists in honing a needle, mounted on a rod on a fine stone until the diameter of the point is less than .01 mm. This may be ascertained by microscopic inspection during honing. Final honing is done on glass by pressing heavily enough on the needle behind the point to bend the needle considerably.

*In practice it was used without a mount by merely resting it on the aircraft window.

The needle is then withdrawn and twisted simultaneously. This is repeated until under inspection the needle looks quite sharp, that is, until the point is of the order of .001 mm. or less. The hole may then be made in tinfoil by gently rotating the sharpened needle point through about one revolution as the point rests on the foil. The tinfoil should be resting on a hard surface such as glass. This technique was successful in producing several reasonably round holes of the order of .005 mm.

This method was abandoned for two reasons. Tinfoil is too fragile, and the hole need not be of such a small diameter. The optimum hole diameter for the pinhole to film distance is computed by the classical formula[1] derived from the condition that the pinhole be about 90% of the diameter of the central zone in a Fresnel zone plate. (This is for best image definition.)

$$a_o = 2\sqrt{\frac{0.9\lambda uv}{u + v}}$$

where u = object distance

v = image distance

when u is very large compared with v, this reduces to:

$$a_o = 2\sqrt{.9\lambda v}$$

if λ is taken as 4000 Å, and v = 2.310 in.

$$a_o = .029 \text{ cm.}$$
$$= .011 \text{ in.}$$

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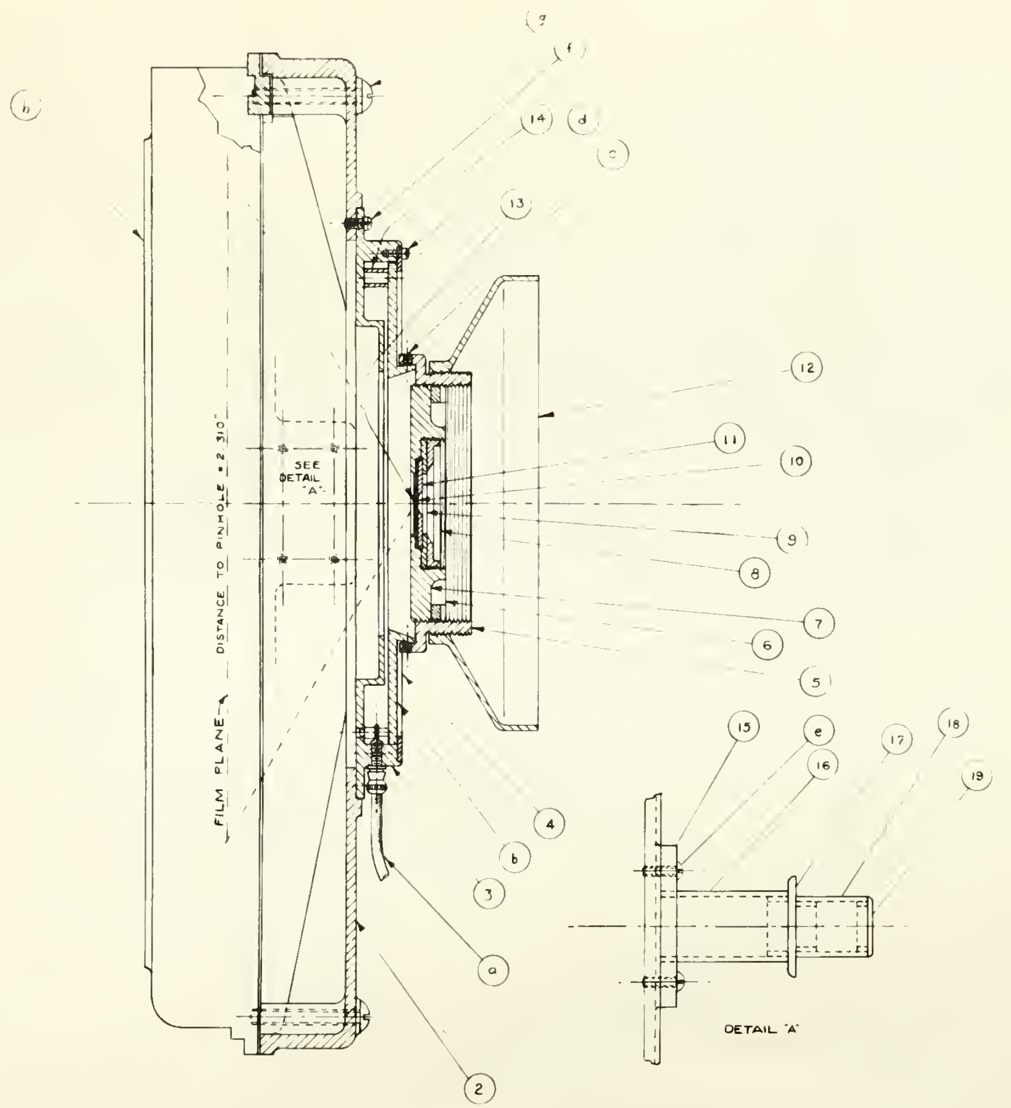
1. Mack, J.E. and Martin, M. J., The Photographic Process, McGraw Hill Book Co., Inc. - 1939

Figure 3.

Assembly Drawing of the Camera



DETAIL "A"

DWG NO	NO REQ.	TITLE
h	1	8"x10" CUT FILM MAGAZINE.
		FAIRCHILD
g	4	#10-32 RD HD SCR. x 1 3/16 LG
f	8	#4-40 FIL HD SCR. x 1/4 LG
39-1-A19	2	END CAP
39-1-A18	2	BEARING SLEEVE
39-1-A17	2	ADAPTER FLANGE
39-1-A16	2	FLANGE SPACER
e	8	#5-40 RD HD SCR x 5/16 LG
39-1-A15	2	MOUNTING FLANGE
39-1-A14	3	SHUTTER SPACER
39-1-A13	1	PINHOLE
d	8	#3-56 FIL HD SCR. x 1/4 LG
c	6	#5-40 SET SCR x 1/8 LG
39-1-A12	1	HOOD
39-1-A11	1	FILTER RETAINING RING
39-1-A10	-	FILTER
39-1-A9	1	WASHER
39-1-A8	1	LOCK RING
39-1-A7	1	PINHOLE & FILTER HOLDER
39-1-A6	1	PINHOLE POSITIONING RING
39-1-A5	1	PINHOLE MOUNTING FLANGE
39-1-A4	1	SHUTTER RETAINING RING
b	1	SHUTTER. LUC SB NO. 25974 AND
a	1	CABLE RELEASE
39-1-B3	1	SHUTTER SUPPORT FLANGE
39-1-C2	1	ADAPTER

BOSTON UNIVERSITY
OPTICAL RESEARCH LABORATORY

TITLE: PINHOLE CAMERA

DRAWN BY	CHECKED	APPROVED	SCALE: FULL SIZE
E F T		Fwo	DWG. NO.
30 JAN 46		Jet. 25 46	39-1-C1

LIMITS OF TOLERANCE
UNLESS OTHERWISE SPECIFIED
FRACTIONAL – ± 1/64
DECIMAL – ± .007
ANGULAR – ± 1/2°

LET.	REVISIONS	DATE	APP.

Figure 4.

Component Parts of the Pinhole Camera

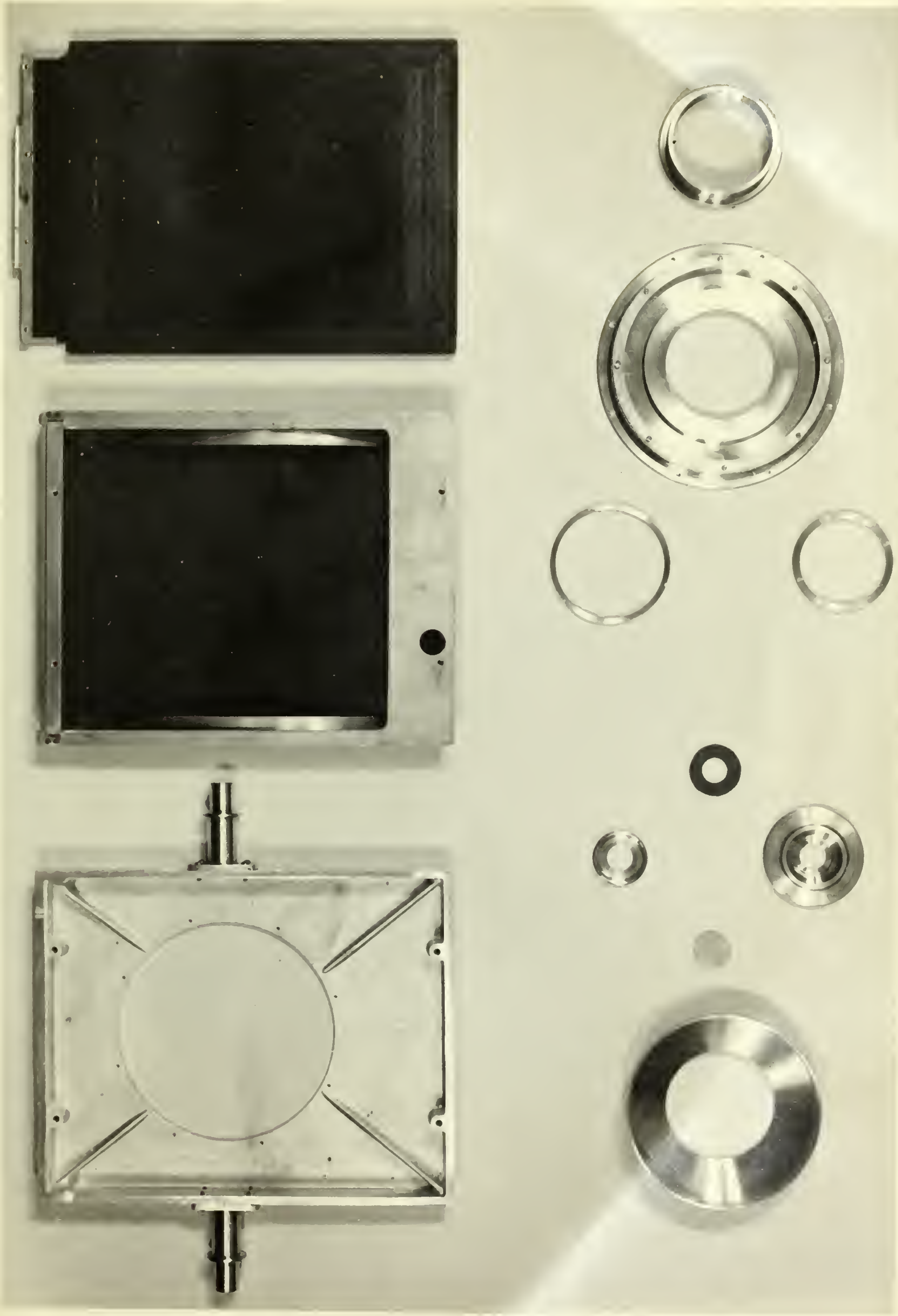


Figure 5.

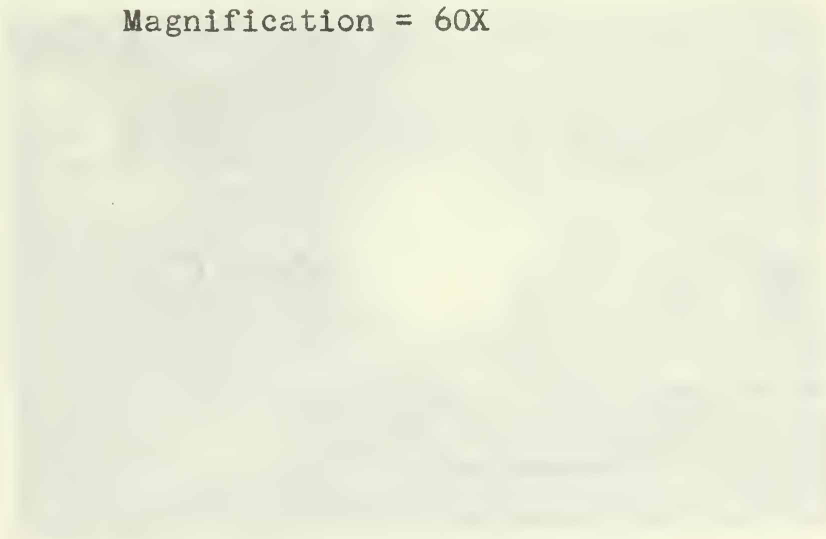
The Assembled Pinhole Camera

Figure 6.

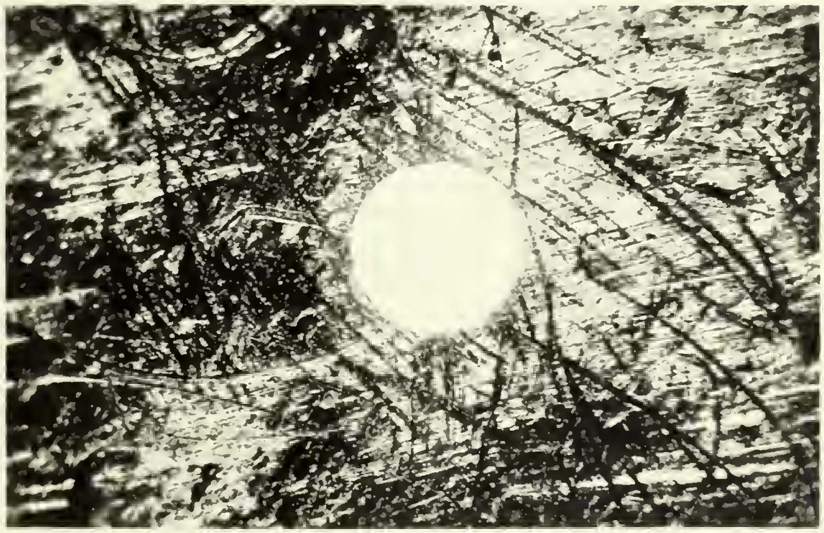
Photomicrographs of a Pinhole Made By
Drilling, Before and After
Cleaning and Polishing

(Hole diameter is .014 inches)

Magnification = 60X



1. PINHOLE IN SHEET BRASS .0015" THICK AFTER DRILLING WITH #80 DRILL.



2. SAME PINHOLE AFTER POLISHING AND CLEANING. HOLE DIAMETER IS .0140"

Figure 7.

Photograph Made With The Pinhole Camera (This photograph, made vertically upwards in a laboratory room, illustrates the extreme wide angle of the camera, and the decrease in illumination toward the edges. The circle limiting the picture is a result of the 120 degree lens hood.)

The method successfully used to produce the good hole .014 inches in diameter was the following: Disks of 1 inch diameter were stamped with a punch and die out of smooth sheets of shim stock brass .0015 inches thick. Several of these blanks were placed in a specially made jig and held tightly together under pressure while the center was pierced by a No: 80 twist drill. The drill diameter is .0135 inches. The best holes were selected from this drilling and the metal burr clinging to the edge was removed by careful stroking with a fine stone. Finally, a tiny sliver of soft pine wood was inserted and rotated gently. Photomicrographs (Fig. 6) show the hole just after drilling and after final cleaning. A series of measurements of the hole diameter made on a Gaertner comparator showed the average diameter to be .0140 inches, with the smallest measured value .0138 inches and the largest .0143 inches. Since these holes were made it has been learned that the cleaning might also be done by using a photo-engraver's etching solution. This would probably round off the edges to some degree.

An interesting and quite different technique was described to the author. An accurately drawn circle, inked in white on a smooth black surface, was photographed at the proper reduction ratio to produce the desired pinhole diameter on the negative. Two identical negatives were made and taped together on three sides emulsion to emulsion, with the dots in exact register. A thin sheet of copper, sensitized on both sides with a standard bichromated

albumen emulsion, was placed between the negatives. This sensitized metal is exposed on both sides. Development in water leaves the metal coated with an etch-resistant albumen emulsion except for the tiny unexposed dot. The hole may then be etched in ferric chloride. Correct exposure and careful control of etching are important. The most difficult part of this technique is getting the two negatives in exact register.

D. Resolving Power Attainable With a Pinhole

As an interesting study, the resolving power for a pinhole may be calculated by the Airy formula for resolving power if we assume that it holds for pinholes as well as lenses. Experiments were performed using a pinhole diameter of .017 inches; pinhole to film distance of 2.56 inches, and a standard U.S.A.F. $\sqrt[3]{2}$ parallel line target, illuminated with sodium light (λ = 5890, 5896 Å).

Experimental values obtained averaged 8.7 l/mm. The value calculated using Airy's formula:

$$N = \frac{10^7}{1.22\,(f/no)\lambda} = \frac{10^7}{1.22\left(\frac{2.56}{.017}\right)5890} = 9.2 \text{ l/mm} \qquad (4)$$

Where N = resolving power in l/mm.

λ = wavelength of light used.

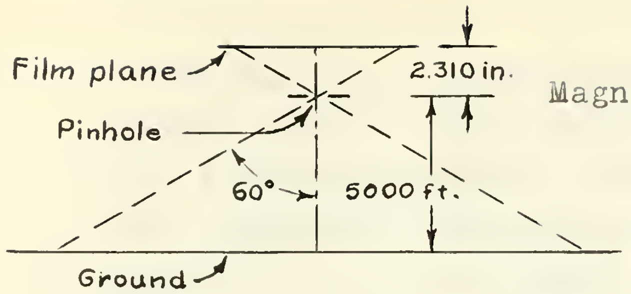
f/no= relative aperture.

The value obtained experimentally is about 95% of the theoretical value.

III. APPLICATION OF THE CAMERA TO THE PROBLEM

In practice, there are two factors that could make haze determination by means of a pinhole camera extremely complicated and tedious. Conditions have been set up that minimize the complexity introduced by these factors without impairing the scope of application. The ideal terrain for haze evaluation exposures would consist of an evenly diffuse reflecting surface. If this were the case, superimposed scattered light would be the only outside factor affecting the variation in illumination over the film plane. Since such an ideal condition is most difficult to obtain, it would appear that in general practice each measurement on the film would need be related to the reflectance of the target or object on the ground before signifigance could be attached to the results. This is obviously a tremendous task.

The necessity for such a procedure can be eliminated through averaging. If exposures are made of a long duration - long enough to allow the image travel on the film to reduce everything to a complete blur, then the scattered light will be super-imposed on an average terrain reflectance, artifically introduced by averaging all the reflectances throughout the extended exposure. For example, at an altitude of 5000 ft., ground speed of 200 mph., image travel in 2 minutes would be 16.2 in., object travel would be 6-2/3 miles. A neutral density filter must be used to compensate for this increased exposure time, else the film would be considerably overexposed. (See fig. 8.)



$$\text{Magnification} = \left(\frac{2.310}{12}\right)\frac{1}{5000}$$

$$= 3.85 \times 10^{-5}$$

Scale = 1:26,000

Figure 8.

Image to Object Ratio at 5000 ft. Altitude

The second factor that was considered: if the solar altitude is low, or terrain is very uneven, then shadows of the projections such as trees, buildings, bushes, and even rocks will cause the terrain to have a lower average reflectance in the direction away from the sunlight path as illustrated in the figure.

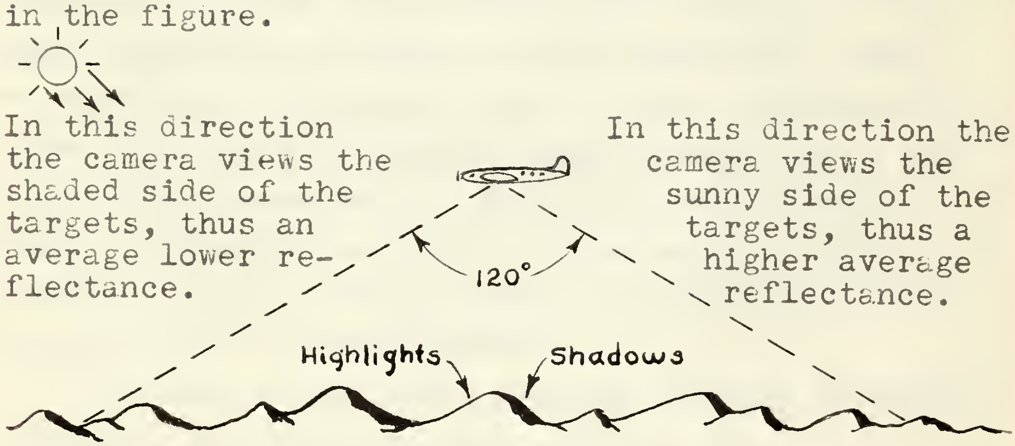


Figure 9.

Effect of Low Altitude Sun On Rough Terrain

This effect can be minimized by choosing the exposure time when the solar altitude is high, and especially by making exposures over even flat terrain, where there will not be deep shadows.

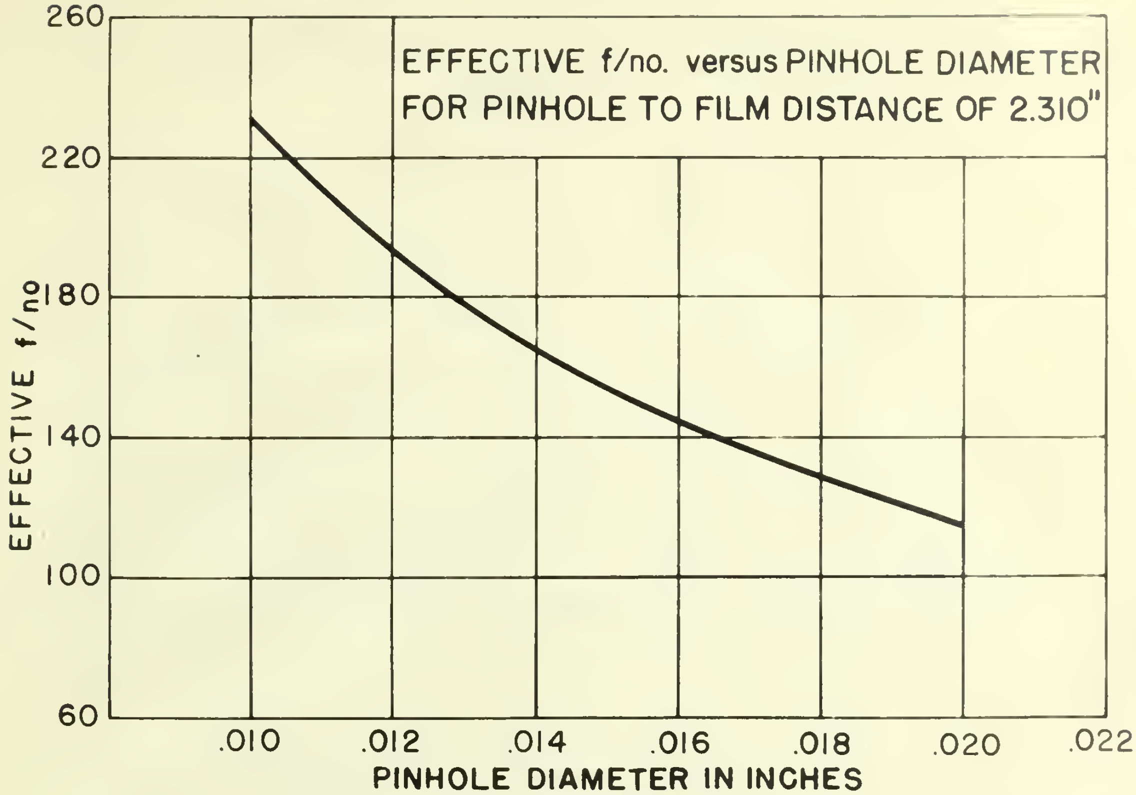
In the first flight tests, exposures using a neutral density filter of 1.3 were made of from 1 to 6 minutes duration. Upon development under the conditions standardized upon, the 2 minute exposures gave a good range of densities, most of which lay upon the straight line portion of the D log E curve. However, these exposures were made in February 1948, over snow covered terrain, where the average reflectance was higher than that of bare ground. From this mission it was also learned that the image travel was not great enough to eliminate completely a slight streaking in the line of flight. So, for these two reasons, a longer exposure time is indicated, especially at higher altitudes where image travel on the film is slower because of increased object distance. The image streaking in the line of flight will never be completely eliminated even by long exposure if there are high contrasts on the ground, but by an averaging process over a series of measurements, these irregularities can be canceled out sufficiently. Again, evenly diffuse reflectance would minimize these irregularities.

For the relationship between pinhole diameter, f/number, and exposure time see fig. 10.

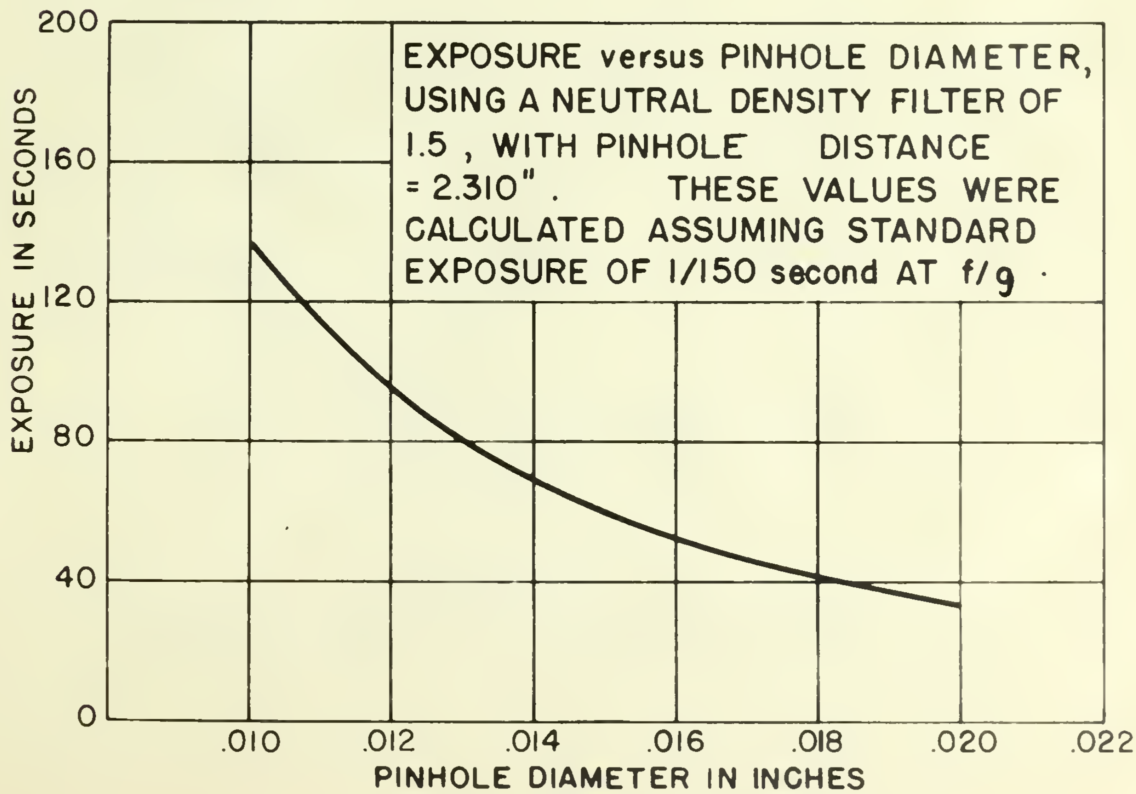
Figure 10.

(a) Graph of Effective f/no. Vs. Pinhole Diameter, When Focal Setting is 2.310 Inches

(b) Graph of Exposure Time In Seconds Vs. Pinhole Diameter, With Neutral Density Filter 1.3, Assuming Standard Exposure Of 1/150 Second at f/9. This Is Calculated Assuming Focal Setting of 2.310 Inches


EFFECTIVE f/no. versus PINHOLE DIAMETER FOR PINHOLE TO FILM DISTANCE OF 2.310"
EFFECTIVE f/no
260
220
180
140
100
60
.010
.012
.014
.016
.018
.020
.022
PINHOLE DIAMETER IN INCHES

(a)


EXPOSURE versus PINHOLE DIAMETER, USING A NEUTRAL DENSITY FILTER OF 1.5 , WITH PINHOLE DISTANCE = 2.310" . THESE VALUES WERE CALCULATED ASSUMING STANDARD EXPOSURE OF 1/150 second AT f/9 .
EXPOSURE IN SECONDS
200
160
120
80
40
0
.010
.012
.014
.016
.018
.020
.022
PINHOLE DIAMETER IN INCHES

(b)

IV. FILM ANALYSIS BY THE USE OF A SENSITOMETRIC WEDGE

Photographic emulsions do not respond linearly (or logarithmically) to an extended range of exposure. (Exposure as is conventional, is defined as the product of intensity and time). In the underexposure region and in the overexposure region, the increase in film density is not related to the exposure by a constant increment in Log E. The figure below represents a typical Density versus Log Exposure plot for a modern high-speed emulsion, developed in a moderately high contrast developer.

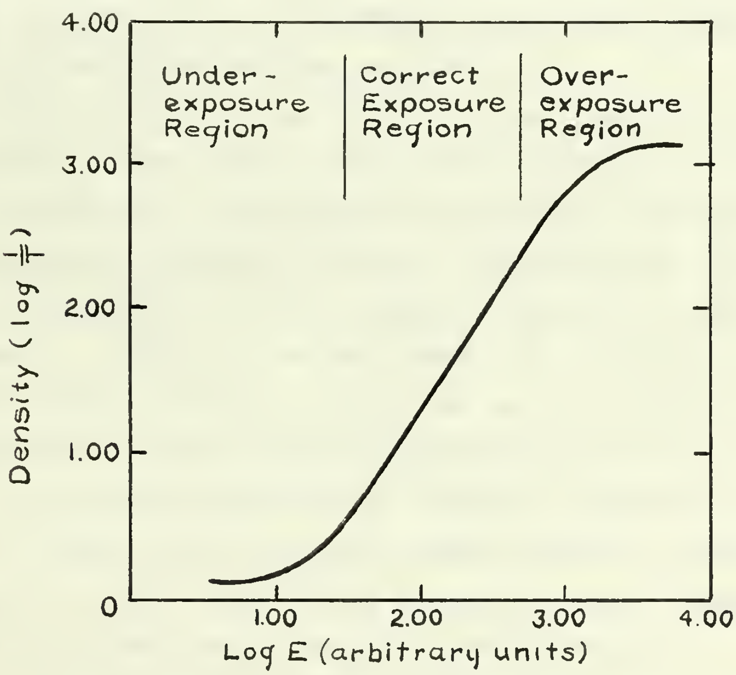


Figure 11.

Typical Density Vs. Log Exposure Curve

Standardization is obtained by exposing a film to a series of different intensities by exposure through a "step wedge", where the intensity increment for each step is accurately known. The characteristic curve for that film and the type processing employed may then be obtained by measuring the corresponding image density for each exposure, and plotting it as in the Fig. 11. Thus, for a given film, the manner of exposure over the focal plane can be determined by including a calibrated series of exposures along an edge to obtain a D log E curve. The densities of the image may then be related to the wedge densities by interpolation from the D log E curve. This is the method used for translating film densities to relative illumination values.

So, in practice the film must have a sensitometric step wedge exposure included in addition to the aerial photograph (actually the circle decreasing in density towards the extreme field angle little resembles the common conception of a photograph). This is accomplished by masking a one-inch width of film along one edge during the camera exposure, then exposing it in a sensitometer developed at the Boston University Optical Research Laboratory to a wedge of 21 steps, whose density increment per step is .15. The D log E curves are obtained from readings made on a Weston densitometer.

Development of these films has been standardized in Eastman Kodak DK-50, for 4 minutes at 68°F. This shorter-than-normal processing time is selected to prevent high film densities since the densitometer accuracy decreases with high film densities.

V. CORRECTION FACTORS

A. Corrections to be Applied to Relative Illumination Curves Of Films to Obtain The Scattered Light Distribution

When the density readings of the film are correlated with the D log E curve of the film to obtain the relative illumination curves over the field angle, these curves must then be corrected for the physical encroachment on the illumination due to the effect of the $\cos^4$ loss, the vignetting due to thickness of the pinhole, and loss caused by filter absorption and reflection. These effects are analyzed and calculated in the following sections, and the overall correction as the product of these separate losses is presented in tabular and graph form. If a test photograph were made of a uniformly bright surface, the relative illumination curve obtained by correlating density with the D log E curve should parallel the total correction curve for the $\cos^4$, vignetting, filter absorption, and reflection.

B. Cos^4 Loss

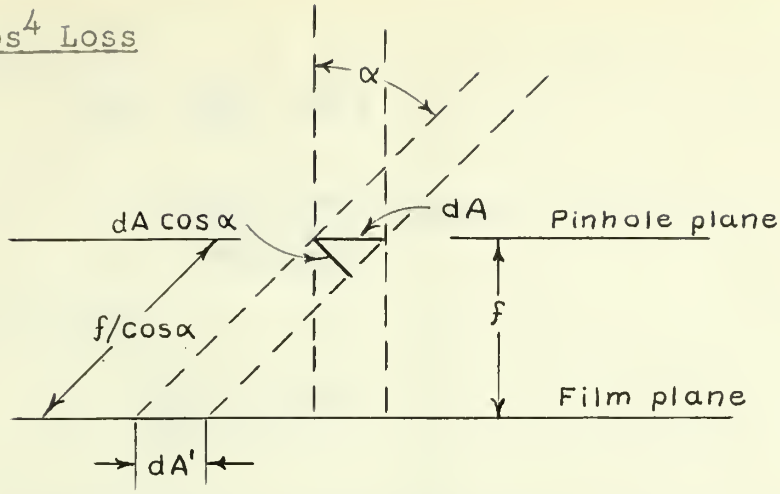


Figure 12.

Parallel Beam Passing Through Pinhole Illuminating Element On Film

α is the angle between the incident beam and the normal to the film plane. Fig. 12.

We may consider the hole as a luminous disk radiating uniformly in all directions. At angle α the intensity is proportional to the projected area, or:

$$dI_{\alpha} = B_o dA \cos \alpha$$

where B_o = brightness

At the film plane the total illumination on element dA' is inversely proportional to the distance $f/\cos\alpha$ squared, and directly proportional to the $\cos\alpha$, since the film plane lies at an angle α with the projected area $dA \cos \alpha$.

Thus:

$$dE_\alpha = \frac{dI\alpha}{d^2} \cos\alpha$$

$$= \frac{B_o dA \cos\alpha}{f^2/\cos^2\alpha} \cos\alpha$$

Integrating,

$$E = \frac{B_o A}{f^2} \cos^4\alpha$$

Since we are interested only in the change in E with α, and the term $\frac{B_o A}{f^2}$ is constant, the relative illumination is proportional to the $\cos^4\alpha$.

C. Vignetting Loss:

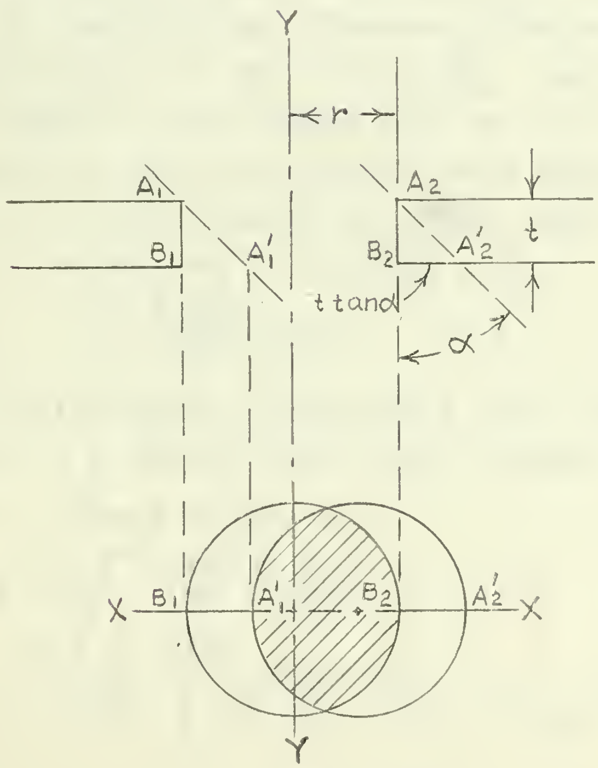


Figure 13.

Plan and Elevation View of the Effect of Vignetting On An Oblique Beam

Since the source is effectively at infinity, we may consider a cylindrical beam through the pinhole.

The illumination on the image plane at any angle is proportional to the cross section area of the beam passing through the hole at this angle.

On page (33), when discussing the $\cos^4$ loss, the cross section through the beam parallel to the sheet in which the hole was punched, was considered to be a circle. However, if the thickness of the sheet is not negligibly small, the cross sectional area of the beam is cut down through the conditions shown in Fig. 13.

The circular front surface A_1A_2 of the pinhole gives way to a beam which would have the cross section $A_1'A_2'$ of identical shape at the rear surface of the pinhole. However, the actual opening in this plane is the circle B_1B_2. Only the shaded area which is the common part of two circles of diameter 2r shifted against each other the amount $t \tan\alpha$, is penetrated by light rays.

To calculate the shaded area:

$$A = \int y\,dx$$
$$y = \sqrt{r^2 - x^2}$$

We integrate along the x axis from the common chord $x = \frac{t}{2}(\tan\alpha)$ (the chord bisects the displacement $t \tan\alpha$) to $x = r$.

$$A = 4\int_{x=\frac{t}{2}\tan\alpha}^{r} \sqrt{r^2 - x^2}\,dx$$

$$A = 4\left(\tfrac{1}{2}\right)\left[x\sqrt{r^2 - x^2} + r^2 \sin^{-1}\left(\frac{x}{r}\right)\right]_{\frac{t}{2}\tan\alpha}^{r}$$

$$A = 4\left[\frac{\pi r^2}{4}\right] - 2\left[\frac{t}{2}\tan\alpha\sqrt{r^2 - \frac{t^2}{4}\tan^2\alpha} + r^2\sin^{-1}\left(\frac{t\tan\alpha}{2r}\right)\right]$$

$$= \pi r^2 - \frac{t\tan\alpha}{2}\sqrt{4r^2 - t^2\tan^2\alpha} - 2r^2\sin^{-1}\frac{t\tan\alpha}{2r}$$

Since $4r^2 = d^2$;

$$A = \frac{\pi d^2}{4} - \frac{t\tan\alpha}{2}\sqrt{d^2 - (t\tan\alpha)^2} - \frac{d^2}{2}\sin^{-1}\frac{t\tan\alpha}{d}$$

Since t is small in comparison with d, we make the approximations:

$$\sin^{-1}\left(\frac{t}{d}\right)\tan\alpha = \frac{t}{d}(\tan\alpha)$$

and $\sqrt{d^2 - (t\tan\alpha)^2} = d$

So:

$$A = \frac{\pi d^2}{4} - \frac{td\tan\alpha}{2} - \frac{d\,t\tan\alpha}{2}$$

$$= \frac{\pi d^2}{4} - td\tan\alpha$$

$$= \frac{\pi d^2}{4}\left(1 - \frac{4}{\pi}\frac{t}{d}\tan\alpha\right)$$

For α = zero, this reduces to $\frac{\pi d^2}{4}$, the area of the circle. The correction term is a function of the thickness, diameter, and angle of incidence.

D. Absorption and Reflection Loss

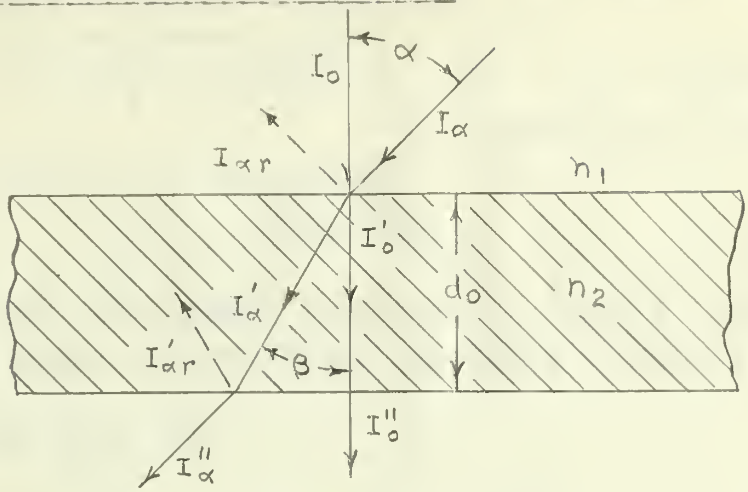


Figure 14.

Cross Section of Filter, Showing Incident And Transmitted Beams

α = angle of off-axis ray with normal

β = angle of refracted off-axis ray with normal

I_o = intensity of on-axis ray

I_α = intensity of ray incident at angle

I'_o = intensity of on-axis ray in filter

I'_α = intensity of off-axis ray in filter

I''_o = intensity of transmitted on-axis ray

I''_α = intensity of transmitted off-axis ray

The ratio of I''_α to I''_o depends upon the absorption characteristics of the filter and the loss due to surface reflections which we desire to calculate for a neutral density filter whose transmission is 0.05 and whose index of refraction is approximately 1.5.

Neglecting reflection losses for the moment, we have;

For the Normal ray:

$$I''_o = I_o e^{-kd_o}$$ (k = unit thickness absorption coefficient)

For the off-axis ray:

$$I''_\alpha = I e^{-kd_o/\cos\beta}$$

since the path length increases as $1/\cos\beta$, where β is the angle the refracted ray makes with the normal.

Dividing I''_α by I''_o:

$$\frac{I''_\alpha}{I''_o} = \frac{I_\alpha}{I_o}\frac{e^{-kd_o/\cos\beta}}{e^{-kd_o}}$$

$$= \frac{I_\alpha}{I_o} e^{-kd_o\left(\frac{1}{\cos\beta} - 1\right)}$$

Since

$$-kd_o = \ln T$$ (T = transmission)

$$= \frac{1}{M}\log T$$ $M = \log_{10} e$

then

$$\frac{I''_\alpha}{I''_o} = \frac{I_\alpha}{I_o} 10^{\cancel{M}\left(\frac{1}{\cos\beta} - 1\right)\frac{\log T}{\cancel{M}}}$$

Since we are assuming even illumination over the field on the filter, the ratio I_α/I_o = unity. The absorption equation then becomes:

$$\log\frac{I''_\alpha}{I_o} = \left(\frac{1}{\cos\beta} - 1\right)\log T$$

or

$$\frac{I''_\alpha}{I''_o} = T^{\left(\frac{1}{\cos\beta} - 1\right)}$$

β is calculated from Snell's law:

$$\sin \beta = \frac{n_1}{n_2} \ (\sin \alpha)$$

For air, n_1 = unity (approximately);

$$\sin \beta = \frac{\sin \alpha}{n_2}$$

$$\text{or } \beta = \sin^{-1} \left(\frac{\sin \alpha}{n_2} \right)$$

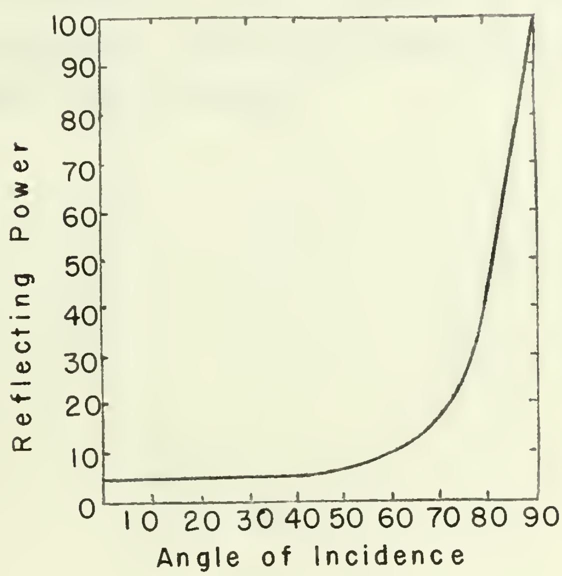


Figure 15.

Variation in Reflecting Power With the Angle Of Incidence For n=1.52 (Hardy & Perrin, "Principles of Optics", McGraw Hill Book Company, 1932)

Reflection loss at both surfaces must be considered also. It is equal at both surfaces, so the fraction of transmitted light must be squared for both surfaces. Values for one surface reflection loss, obtained from the figure above, are again computed considering the

intensity of the perpendicular beam units, since we are concerned only with relative transmission.

On the following page is a table of the corrections for the $\cos^4\alpha$, vignetting, filter absorption and reflection losses, computed at equal increments of k ($\tan\alpha$), from zero to 10, by means of the equations developed in the preceding sections. The values in the last column are the products of the three corrections in the preceding columns, and represent the total corrections to be applied to the illumination curves obtained from correlation of film densities with the D log E curve.

E. Table of Correction Factors:

Table I

Correction Values to be Applied to Illumination Values Determined by Correlating Density With D log E Curve

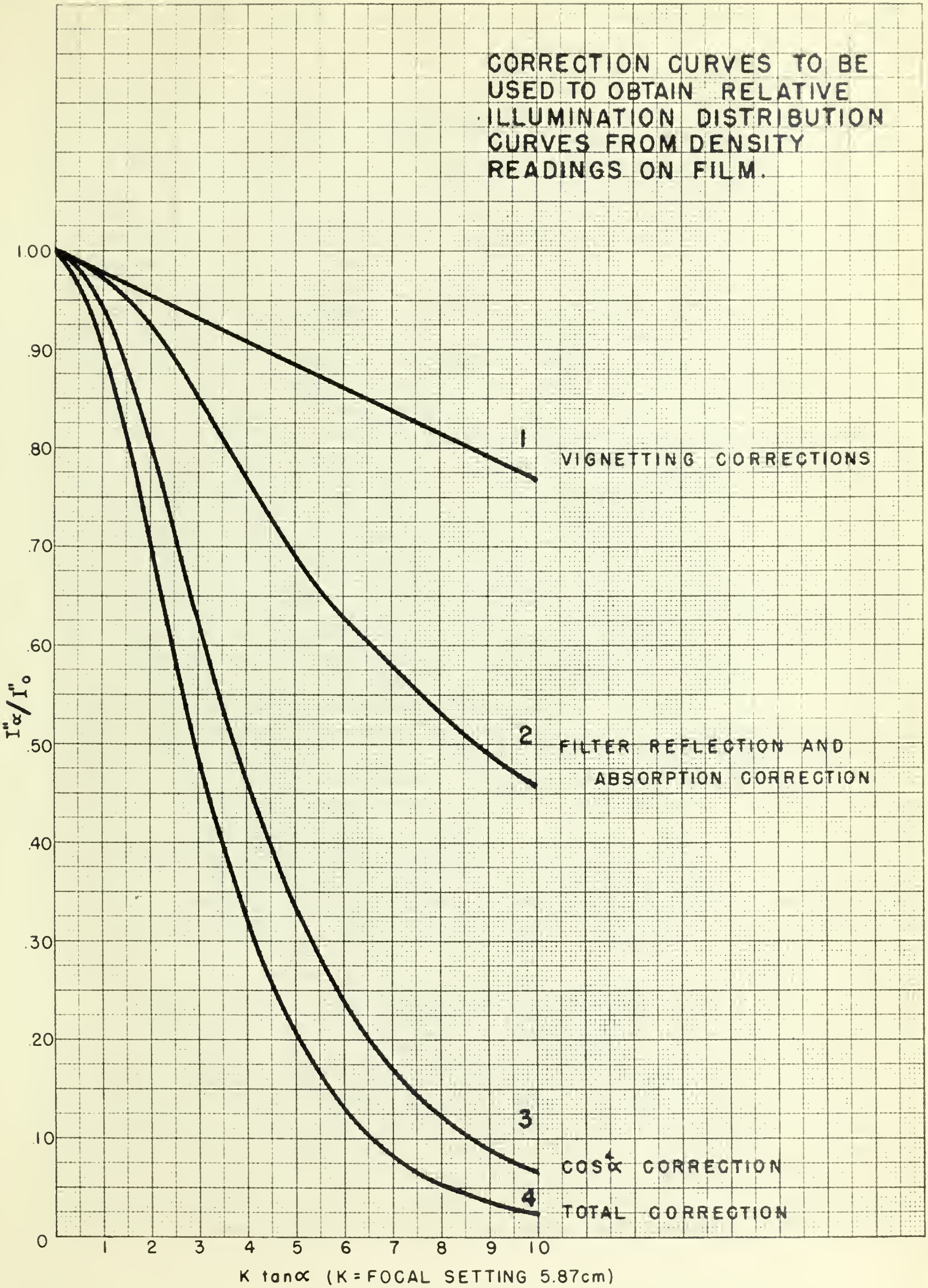
k tan α k=5.87 cm	$\cos^4\alpha$	Vignetting	Filter*	Combined Corrections**
0.0	1.000	1.000	1.000	1.00
1.0	.944	.977	.971	.90
2.0	.803	.954	.922	.71
3.0	.628	.930	.845	.49
4.0	.466	.907	.776	.33
5.0	.336	.884	.692	.21
6.0	.239	.861	.629	.13
7.0	.170	.837	.580	.082
8.0	.122	.814	.532	.053
9.0	.089	.791	.492	.035
10.0 ($\alpha=59.6^\circ$)	.065	.768	.458	.023

* Filter absorption and reflection

** Combined correction for $\cos^4\alpha$, vignetting, filter absorption and reflection.

Figure 16.

Graph of Corrections To Be Used
To Obtain Relative Illumination
Distribution Curves From
Density Readings of
Film


CORRECTION CURVES TO BE USED TO OBTAIN RELATIVE ILLUMINATION DISTRIBUTION CURVES FROM DENSITY READINGS ON FILM.
1 VIGNETTING CORRECTIONS
2 FILTER REFLECTION AND ABSORPTION CORRECTION
3 COS⁴α CORRECTION
4 TOTAL CORRECTION
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
1 2 3 4 5 6 7 8 9 10
I"α/I"o
K tanα (K = FOCAL SETTING 5.87cm)

VI. FLIGHT TESTS

On January 8, 1948 the pinhole camera was flight tested in conjunction with other laboratory projects in spite of the fact that the camera had not been completed in time to make laboratory tests.

On the first flight, exposures ranging from 30 tO 90 seconds were made at altitudes ranging from 5,000 to 20,000 feet. A neutral filter of density of 1.00 was used. The weather was cold and clear, with excellent visibility and little haze apparent. Upon processing, all the exposures revealed light leaks around the edge of the magazine. A first attempt was made later in the laboratory to eliminate these light leaks by covering all suspicious areas with thin layers of felt. Also, in some of the exposures on this flight, the shutter was not operating properly.

Results from a flight two days later made under similar operating and weather conditions, showed that some light leaks were still in evidence. These were completely eliminated after this mission by replacing the felt with mohair.

A slight dark ring on the test films of about 4 inches radius was discovered to be caused by reflection from one of the retaining rings that had not been blackened. Flat black paint eliminated this.

Films from a third flight on January 13, 1948 showed that the light leaks were eliminated. Exposures were made through a neutral density filter of density 1.3 under the same weather and operating conditions as the previous missions. These exposures

revealed that either the image travel was not sufficient or the object contrast on the ground was too high to eliminate streaking. This indicates that exposure times needed to be increased and terrain carefully chosen.

The exposures on these first test flights were all developed without including a sensitometric wedge exposure, since the sensitometer at the laboratory was not yet in operating condition. When it was available, strips of the same emulsion number film were exposed, and then processed under identical conditions as the aerial exposures. The D log E curves obtained thus were used to interpret some of the aerial films. The analysis was not carried out for all films since the processing of the step wedge and the photographs at different times and with a different batch of developer introduces an unknown error. These first flight tests were not made with the idea of gathering significant data for haze evaluation, but merely to test the camera and determine exposure levels for future flights when the sensitometric exposure could be included on the same film. Since these first flights were made, the sensitometer has been completed and a new and faster densitometer has been secured.

The following data and graphs were obtained from an exposure made over snow-covered terrain at 5000 feet, on January 13, 1948 at 11:50 A.M. at a latitude of approximately 42°N. The weather was sunny and clear, with excellent visibility, and very little apparent haze.

Although these films show little haze, they do show a

general increase in the illumination in the North and a sharp increase at extreme angles in the East. The plane heading was 50°, so the irregularities caused by streaking are about equal in magnitude in the North-South, East-West graphs.

The terrain consisted of gently sloping hills. The irregular nature of the terrain may have caused in part the departures from a smooth curve, especially in the absence of any appreciable haze.

Departures in the graph from a smooth curve arise in part from the streaked nature of the films.

VII. CONCLUSIONS AND RECOMMENDATIONS

The instrument described in this paper when used as prescribed, provides a means for determining the relative distribution of scattered light over a solid angle of π steradians, or a total field angle of 120 degrees. It can be applied to determining the relative amounts of scattered light at various altitudes and in various kinds of weather. By using various selective filters, the relative amounts of scattered light in the blue, green, and red, may be determined. Its accuracy depends on correct calibration by means of a sensitometric wedge, quality of the pinhole, and choice of terrain.

Results from one single exposure cannot be taken as an exact representation of the energy distribution because of irregularities introduced through uneven terrain reflectance; but from a series of observations made under the same conditions, a true representation of the distribution may be obtained

by applying a suitable averaging process.

It is recommended that a series of missions be flown during which many exposures be made through a range of varying altitudes in various degrees of haze. Precise records must be kept of all pertinent data, such as:

1. Time at which exposure was made.
2. Kind of weather, including visibility, cloud conditions, air mass movement, wind velocity, temperature, and humidity.
3. Exposure time.
4. Filters used.
5. Aircraft path, heading and speed of aircraft.
6. Type and terrain over which exposures are made.
7. Film position with respect to heading.
8. Emulsion numbers and types employed.

Exposures must be made through an open window to avoid an additional error introduced by window absorption and reflection.

It is planned to make such flights this summer (1948) to employ the techniques and instrument described in this paper, for the evaluation of atmospheric haze.

The tables on the following pages present data that were obtained from an aerial exposure (details of which are on the title page for Fig. 17(a)) by correlating the densities with the D log E curve. The first column k tan α (k=5.87 cm.) represents the 5 mm. intervals from the center of the film at which readings were made. The figures in the second column are the illumination values on the film as obtained from the log E values. In the third column corrections for the $\cos^4$, vignetting, and filter reflection and absorption have been applied the illumination values. (See Table I.)

Table II is a reading in the North-South cross-section.

Table III is a reading in the East-West cross-section.

Table II

Uncorrected and Corrected Values For Illumination Vs. k tanα
In The North-South Plane

Center to North:

k tan α	E (uncorrected)	E (corrected)
0	100 %	100 %
.5	100	104
1.0	97.6	107
1.5	82.1	101
2.0	72.4	102
2.5	53.6	90
3.0	51.2	105
3.5	38.9	96
4.0	33.1	100
4.5	28.8	111
5.0	23.4	111
5.5	19.0	90
6.0	15.5	120
6.5	12.6	122
7.0	9.55	116
7.5	8.32	124
8.0	6.60	125
8.5	5.36	121
9.0	4.26	122

Center to South:

0	100.0 %	100 %
.5	100.0	104
1.0	93.2	104
1.5	81.2	100
2.0	67.5	94
2.5	60.2	101
3.0	52.5	105
3.5	41.6	103
4.0	33.1	100
4.5	27.5	106
5.0	21.2	101
5.5	17.0	102
6.0	14.0	108
6.5	10.5	102
7.0	9.11	111
7.5	7.24	108
8.0	5.75	108
8.5	4.37	100
9.0	3.23	92

Figure 17 (a)

Graph of the Relative Intensity of Illumination (Center Intensity = 100%) In The North-South Cross Section

Field angle 120°, altitude 5,000 ft., exposed for 2 minutes at 11:50 A.M. on Jan. 13, 1948. Weather clear with unlimited visibility, bright sunshine. Taken enroute from New York to Boston at a latitude about 42°N, over hilly terrain covered with freshly fallen snow.

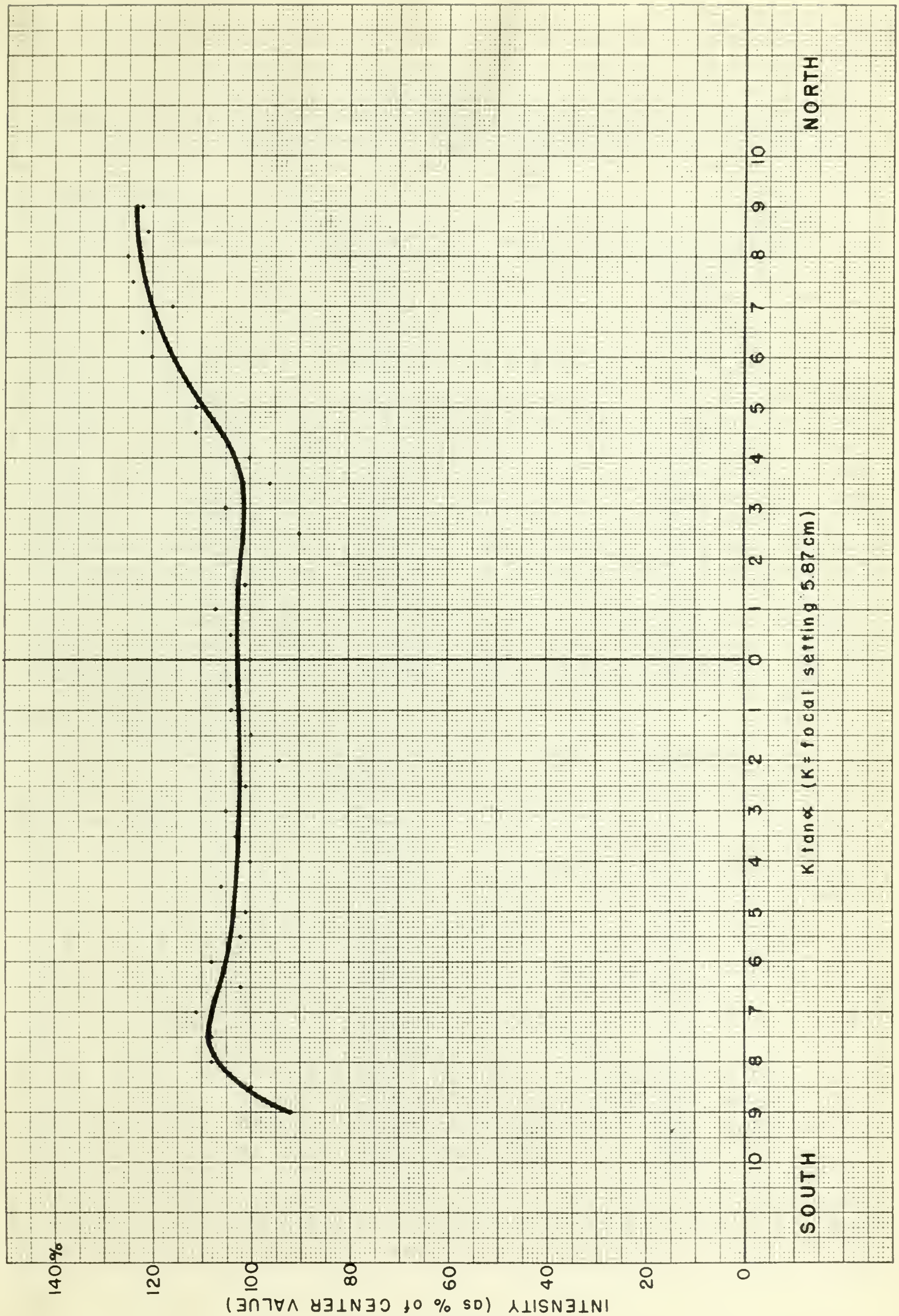

NORTH
SOUTH
K tan α (K = focal setting 5.87 cm)
INTENSITY (as % of CENTER VALUE)
140%
120
100
80
60
40
20
0
10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
9
10

Table III

Uncorrected and Corrected Values For Illumination Vs. k tan α In The East - West Plane

Center to East:

k tan α	E (uncorrected)	E (corrected)
0	100. %	100 %
.5	100.	104
1.0	92.7	103
1.5	86.6	106
2.0	66.0	93
2.5	58.9	99
3.0	47.1	96
3.5	36.1	89
4.0	32.0	97
4.5	26.0	100
5.0	22.0	105
5.5	19.1	114
6.0	14.0	108
6.5	11.0	107
7.0	8.8	107
7.5	7.9	118
8.0	6.9	130
8.5	6.2	141
9.0	4.9	140

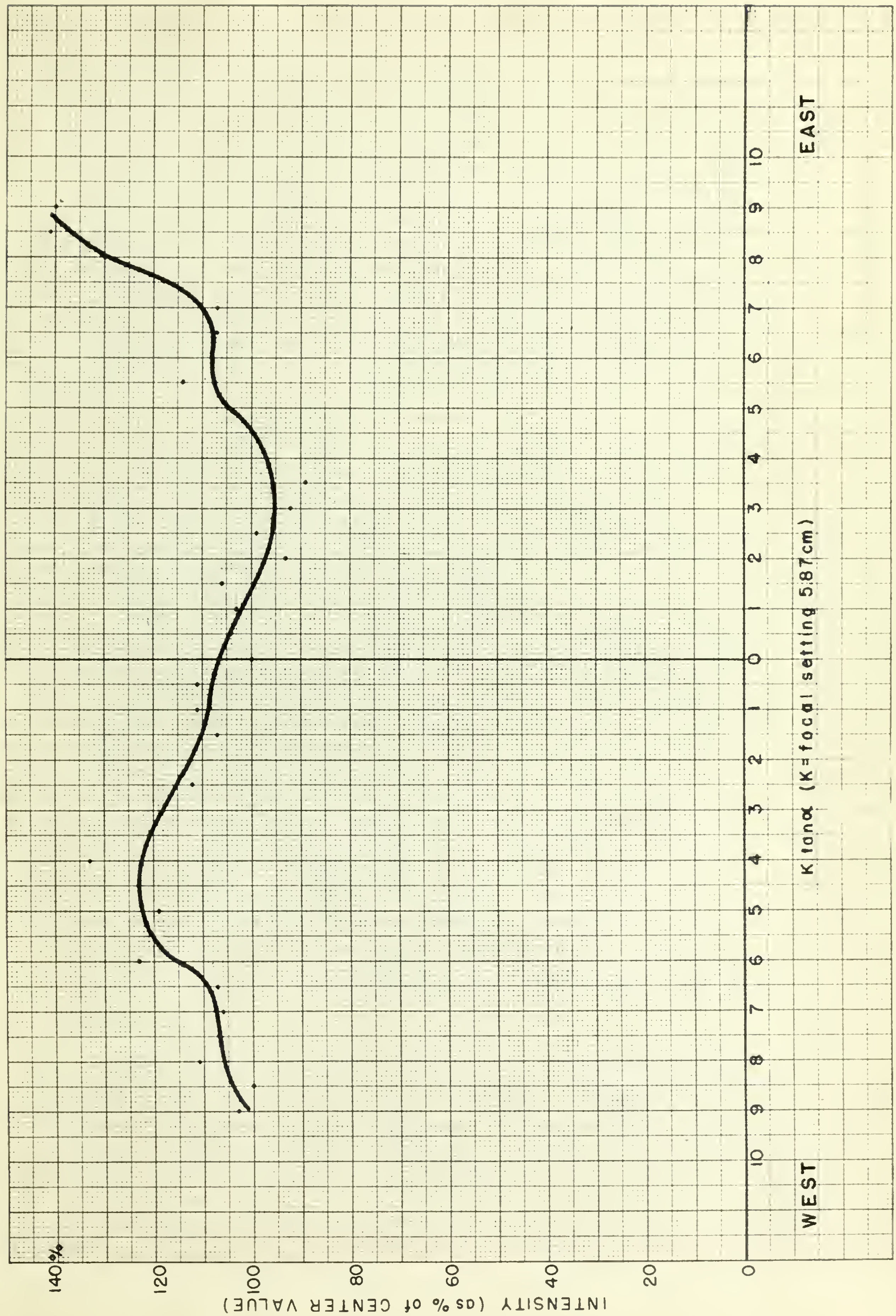
Center to West:

0	100 %	100 %
.5	107	111
1.0	100	111
1.5	87.2	107
2.0	68.8	97
2.5	66.4	112
3.0	57.8	118
3.5	49.0	121
4.0	43.9	133
4.5	32.1	123
5.0	25.0	119
5.5	20.1	120
6.0	16.0	123
6.5	11.0	107
7.0	8.7	106
7.5	7.2	107
8.0	5.9	111
8.5	4.4	100
9.0	3.6	103

Figure 17 (b)

Graph of the Relative Intensity of Illumination (Center Intensity = 100%) In The East-West Cross Section

(For pertinent data see Fig. 17 (a))


INTENSITY (as % of CENTER VALUE)
140%
120
100
80
60
40
20
0
WEST
EAST
10
9
8
7
6
5
4
3
2
1
0
K tan α (K = focal setting 5.87 cm)

VIII. ABSTRACT

The purpose of this paper is to describe the research on design, construction, and preliminary testing of a pinhole camera for evaluation of the relative distribution of scattered light from atmospheric haze. The camera is designed for airborne use, and intended to make photographs covering a field angle of 120 degrees, at a series of altitudes.

The introduction includes a brief discussion of haze and the theory of scattering, also the effect of sun position and altitude upon the scattered light distribution as well as the effect of haze upon aerial photography.

The camera, as it was designed to meet the requirements set up for it, is shown in photographs and assembly drawings. The camera will provide photographs which, upon analysis, show the variation in the superimposed scattered light upon an average terrain reflectance over a field angle of 120 degrees. To achieve this average terrain reflectance the exposure is made of sufficient duration to blur all image detail in the film, while the aircraft maintains a constant heading with respect to the sun. To compensate for the increased exposure time, a neutral density filter is used with the pinhole.

To translate the densities of the photograph into terms of relative illumination incident on the film, a sensitometric exposure is included on each film; from this, the densities can be translated

into terms of relative exposure. Values so obtained will include the fall-off of illumination due to the physical characteristics of the camera. These inherent losses are due to Lambert's law, vignetting of the off-axis beam because of the thickness of the material in which the pinhole is made, and the absorption and reflection characteristics of the neutral density filter. These losses are calculated, and correction tables and graphs are shown that are used in separating the desired haze effect from the inherent illumination fall-off.

Graphs of pinhole effective f/no. and exposure time versus pinhole diameter are included, also a photograph made in the laboratory to demonstrate the extreme wide angle of the camera. Readings and a graph of a test film are presented and discussed.

The method is a new approach to making measurements of scattered light in the atmosphere. If carried through an organized program of flights and analysis, may prove to be an important tool for the scientist.

BIBLIOGRAPHY

Clark, Walter	Photography By Infra-Red Wiley Book Co., 1946
Clewell, Dayton	Scattering of Light By Pigment Particles - from J.O.S.A. August 1941
Hardy, A.C. and Perrin, F.H.	Principles of Optics McGraw Hill, 1932
Jenkins, E. A. and White, H. E.	Fundamentals of Physical Optics McGraw Hill, 1937
Mack, J.E. and Martin, M.J.	The Photographic Process McGraw Hill, 1939
Mees, C.E. Kenneth	The Theory of the Photographic Process - Macmillan, 1945
Neblette, C.B.	Photography - Its Principles and Practice -D. Van Nostrand Co., Inc., Fourth Edition 1942
Sears, F.W.	Principles of Physics - Vol. III Optics - Addison Wesley Press, Inc. 1945

The following Reports are listed by code number only, because of military classification.

Wright Field Air Force Reports

Photo Lab. Eng. 59-677-22-2
Photo Lab. Eng. 59-677-22-4
Photo Lab. Eng. 59-677-22-5

British Reports

WA 2396-2	APRC 81
WA 2396-2B	APRC 82
WA 2396-2C	APRC 99
	APRC 173